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Benchmark studies on the treatment of residual stresses in fracture assessments of pressure vessels

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ABSTRACT

The objective of the work reported here is to assess the accuracy of the procedures for the treatment of residual stresses in the fracture evaluation of pressure vessels, highlighting new developments in the methods employed. The participating members consist AEA-Technology plc. (United Kingdom), SIEMENS (Germany) and FRAMATOME (France). This work represents a study contract [1] from Activity Group 2 of the Working Group on Codes and Standards in the framework of the DGXI of the Commission of the European Communities.

INTRODUCTION

The aim of the study is to apply and compare procedures for the treatment of residual stresses in fracture assessment. In order to make meaningful comparisons it was decided that where possible all other parameters in the calculations such as geometry, material properties and stress analysis etc. should be the same.. With this in mind, participating members were requested to produce and submit benchmark problems with the following data supplied:

-all neçessary geometry definitions
-a-full details of stress analysis including primary, secondary and residual stresses.

Each member also supplied a validation solution (by Finite element, experiment etc.) for their benchmark. All members then produced solutions for the benchmarks. The analytical methods used are described briefly here, more detail is given in [1].

BENCHMARK PROBLEMS

Full details of the respective benchmarks are given in [1].

AEA Technology Benchmark (FBR vessel with through-wall crack)

The problem requires the calculation of the critical crack size for a part-circumferential through-wall flaw at a double-sided girth weld in an FBR stainless-steel vessel. Only the initiation of ductile tearing is considered i.e. the tearing resistance is not modelled.

Vessel geometry	Vessel parent material data:
Vessel wall thickness=50mm	Young's Modulus E=192500 MPa
Vessel internal radius=700mm	Poisson's ratio ν=0.3
	0.2 % Proof stress=233 MPa
	Ultimate tensile stress=363 MPa

Vessel weld material ductile tearing initiation toughness $K_{(\Delta a=0.2mm)} = 150$ MPa$\sqrt{m}$.

The primary axial and hoop stresses are 30 MPa and 60 MPa respectively. Secondary stress due to double sided girth weld is a cosine through-wall distribution limited to peak value of the 0.2 % proof stress of the vessel parent material. The resulting residual stress pattern is shown in Figure 1.

Framatome Benchmark (BMW with external full-circumferential crack)

The objective of this benchmark is to evaluate the J-Integral for a crack located in a Bi-Metallic-Welded (BMW) joint under given material properties and loading conditions.The BMW is between stainless steel and ferritic steel cylindrical structures of (see Figure. 2). The cylinder has an internal radius, Ri, of 638mm, thickness of 93.7mm and length of 10000mm.The weld is located in the centre region with a fully circumferential crack of 8 mm depth situated on the outer surface of the cylinder on the austenitic side at 0.1 mm from the interface.

Stainless steel (Type 316L) material properties	Base Metal (Type 508 cl3) properties
E=176500 MPa	E=191500 MPa
ν=0.3	ν=0.3
Sy=245 MPa	Sy=454 MPa

The loading consists in applying a secondary residual stress, then a primary axial stress. Three values of primary stress (107 MPa,Case 1; 207 MPa, Case 2; 274 MPa, Case 3) are considered with the same distribution of residual stress shown in Figure 4.

Siemens Benchmark (under-clad crack in an RPV)

The objective of this problem is the calculation of the fracture mechanics parameter (J-Integral, stress intensity factor KI) for a given sub-surface crack in a cladded Reactor Pressure Vessel (Figure 3). The vessel is loaded by internal pressure (primary membrane stress) and temperature loading (secondary stress) in addition to the residual stresses.(Figure 5 for various stresses). The vessel has an inner radius of 2180mm, with a base metal thickness of 221 mm and a cladding thickness of 6mm. The crack depth, a, is 10mm and the crack length, 2c, is 60mm.

Vessel base metal (ferritic material) properties	Austenitic cladding properties
E=199000MPa	E=194000 MPa
ν=0.3	ν=0.3
Sy=450 MPa	Sy=328 MPa
Su=645 MPa	Su=485 MPa

ANALYTICAL METHODS USED BY AEA TECHNOLOGY

AEA Technology has used the R6 procedure by Milne et al. [2] option 1 where the parameters Kr and Lr are calculated to determine the proximity of the structure to failure by linear elastic fracture and plastic collapse, respectively.

Benchmark on FBR vessel with through-wall crack

The stress intensity factor (SIF) solutions for internal pressure loading and the cosine distribution self-balancing residual stresses were taken from Green and Knowles [3]. The limit load solution used was that given by Miller [4]. For the validation results on this benchmark, Finite element analysis was carried out using ABAQUS code with a mesh refinement as used by Green and Knowles [3].

Benchmark on BMW with external full-circumferential crack

For this problem, the Guidance in R6 [2] states that the data for tensile yield stress, used in the calculation of limit load, should be representative of the weakest constituent in the vicinity of the flaw i.e. using the Stainless steel properties. Guidance on evaluation under mode-I mode-II and mode-III loads was taken from R6. Since no fracture toughness data was given in the problem, it was assumed that the fracture toughness to yield stress ratio criterion Kmat/Sy>=0.2 $\sqrt{m}$ was met.

Benchmark on the under-clad crack in an RPV

In this case, since the solutions for SIF and limit-load were not readily available, the defect was re-characterised as surface breaking defect, increasing the depth of the defect by the thickness of the cladding whilst maintaining the crack depth to length ratio of the sub-clad defect, Marshall [5].

ANALYTICAL METHODS USED BY FRAMATOME

Benchmark on FBR vessel with through-wall crack

The method used to determine the critical crack length of a part-circumferential through-wall defect in a pressure vessel is based on GE-EPRI Handbook type method by Kumar et al.[6] where the elastic-plastic solutions for the J-parameter are given for a Ramberg-Osgood representation of the material, as a function of applied load, crack length, and the limit load of the structure which in this case is given by Miller [4]. The effect of residual stresses is considered in a rough manner, as given by a plate solution Green and Knowles [3].

Benchmark on BMW with external full-circumferential crack

The method developed to treat this problem is named Kj method which is in part based on the two-parameter approach used in the R6 procedure [2].

Benchmark on the under-clad crack in an RPV

The method used to compute the fracture mechanics parameters for a given sub-surface semi-elliptical flaw in a cladded pressure vessel is to treat the defect as an elliptical embedded flaw and use the analytical solution corresponding to a strip crack and correct it through shape and surface factors.

ANALYTICAL METHODS USED BY SIEMENS

Benchmark on FBR vessel with through-wall crack

Because the residual stresses are self-balancing across the thickness and the material behaviour is supposed to be ductile, an initial estimate of the critical crack length ignored residual stresses, applying a flow stress and limit load approach Bartholomé [7].

Additional calculations were performed assuming that the residual stresses of the magnitude of the yield stress contributes to the stress intensity factor, a KI- calculation according to Raju-Newman [8] is performed. The load input is taken as membrane load of 30 MPa, bending load of 233 MPa. A plastic corection according to ASME Code (1995) is used for comparison.

Benchmark on BMW with external full-circumferential crack

This problem is solved by applying two different approaches namely: 1) the KI method with and without plastic zone correction and 2) the elastic plastic J-Integral calculation.

1)The SIF are calculated using the idealized stresses . These consist of the membrane axial stresses, which are constant across the wall thickness and the residual stresses, which have a peak at the outer surface. Both stresses are superposed and the three cases (case 1 to case 3) differ in the magnitude of the membrane stress. The KI factors are calculated according to Newman-Raju [8] where a plastic zone correction according to ASME Code 1995 is calculated taking the yield stress of the base metal and of the Stainless steel.

2)The J-Integral for a circumferential surface flaw is calculated using the program pc-crack [9]. Because only membrane stresses can be input, the stress gradient over the wall-thickness is integrated along the crack depth and added to the membrane stresses.

Benchmark on the under-clad crack in an RPV

This is a thermal shock problem and it is solved by a three-dimensional finite element analysis. The semi-elliptical sub-surface crack is postulated at the interface of cladding and base metal. The problem is solved with the computer code ADINA. In addition, simplified methods [8] are applied where the semi-elliptical sub-surface crack is treated as a surface crack ignoring the cladding.
The procedure is described in the German Rules KTA 3201.2 for NPP (1990)

RESULTS OBTAINED

Table I shows the results of the solutions for the benchmark on the FBR vessel with a part-circumferential through-wall flaw. Reasonable agreement is obtained between the Framatome limit-load based calculations and the limit-load/flow-stress calculations of Siemens. The full assessments by AEA Technology and Framatome, incorporating the SIF solutions by Green and Knowles (1992) and accounting for the plasticity effects, and the elastic toughness calculations by Siemens, were in reasonable agreement with the finite element result. Elastic toughness calculations including plasticity effects by Siemens gave rather too conservative values (-28%).

Table II summarises the results for the benchmark on the Bi-Metallic-Welded joint.The Framatome simplified analysis results are in good agreement with the Finite-element validation results; also the simplified results are always conservative.

The simplified analysis made by AEA Technology, following the R6 Guidelines (using weaker material properties) are conservative but with rather large margins. However, if one uses the base material data for the analysis, results are still conservative for two load cases (+17% in case 1 and +7% in case 2) but become non-conservative for the 3rd case (-49%).

The Siemens submission recommends that the most reliable results are those from the KI method using plastic zone correction and stainless steel properties. However, when compared with the Finite-element results, although case 1 and 2 are conservative by +22% and +29% respectively, the case 3 results are non-conservative by -29%.The elastic-plastic J-Integral method results using E and v of the stainless steel give better agreement with the Finite-element results, with case 1 being non-conservative by -16% but cases 2 and 3 being conservative by 20% and 25% respectively.

Table III summarises the results for the benchmark on under-clad crack in an RPV. The AEA Technology solution where the crack is recharacterised as a surface defect with the depth increased by the thickness of the cladding shows the greatest values of SIF. The Framatome results only differ by 3% between the two points considered and are in good agreement with the AEAT results on surface crack ignoring clad, and Siemens results using elastic analysis or elastic-plastic correction. However, all these results are conservative with respect to the finite element results.

CONCLUSIONS

For the benchmark problem concerning the part-circumferential through-wall defect in the FBR RPV, good agreement was obtained between the simplified solutions and the Finite-element validation.

For the problem on a Bi-Metallic-Welded joint, good agreement was obtained between the Framatome simplified solution and the Finite-element validation results. Results of recommended simplified analysis by AEA Technology were conservative with margins upto 50%. The recommended simplified solution (K(J)) by Siemens was conservative on basis for cases 1 and 2 by 22% and 29% respectively but non-conservative for case 3 by -16%.

For the problem of under-clad in an RPV good agreement was obtained between the AEA Technology, Framatome, and Siemens simplified analyses results. However these results are quite conservative with respect to the finite-element results.

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Table I Results for Benchmark on FBR vessel with through-wall crack:

Organisation	Critical crack length, 2c, (mm)	Analysis/Comments
AEA Technology	1253	R6 Procedure , full assessment including effects of plasticity
AEA Technology (validation)	1400	Finite Element , elastic-plastic ananlysis
Framatome	2199	Limit load approach
	1660	Elastic toughness calculation, ignoring residual stress
	1350	Full assessment including effects of plasticity
Siemens	2463	Flow stress method
	2243	Limit load approach
	1433	Elastic toughness calculation
	1010	Elastic toughness calculation including plasticity effects

Table II Results for Benchmark on BMW with external full-circumferential crack

	KJ (MPa√m)			
Organisation	Case 1	Case 2	Case 3	Analysis/Comments
AEA Technology	52.55	102.83	264.1	Simplified Analysis
Framatome	48.7	79.72	188.06	Simplified Analysis, Kj method
Framatome (validation)	42.4	66.7	176.2	Finite element analysis
Siemens	43.52	63.1	75.0	KI method without plastic correction
				KI method with plastic correction
	43.52	64.55	79.98	E and υ taken for Type 508
	51.74	86.3	124.49	E and υ taken for SS
				Elastic-plastic J-Integral
	34.63	53.89	67.11	E and υ taken for Type 508
	35.78	80.00	220.6	E and υ taken for SS

Table III Results for Benchmark on the under-clad crack in an RPV

Organisation	KJ (MPa√m)		Analysis/Comments
	Surface Point	Deepest Point	
Framatome	75.75	78.2	Simplified analysis
	79.13	81.71	Strip crack
AEA Technology	79.63	108.58	Surface crack increased by clad thickness
	58.36	82.94	Surface crack (ignoring clad)
Siemens	50.35	75.41	Simplified analysis, elastic
	56.83	83.52	elastic-plastic correction
Siemens (validation)	35.5	57.7	Finite element

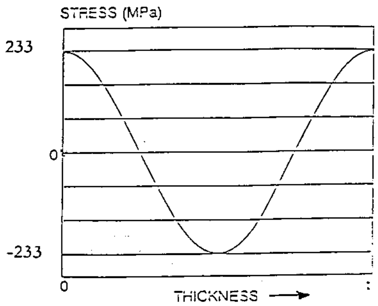

Figure 1

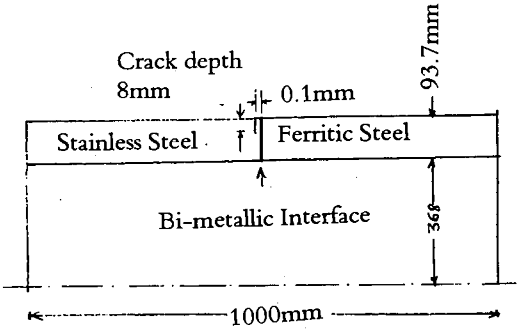

Figure 2

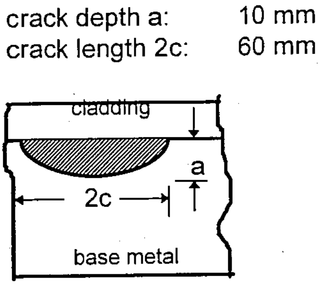

Figure 3

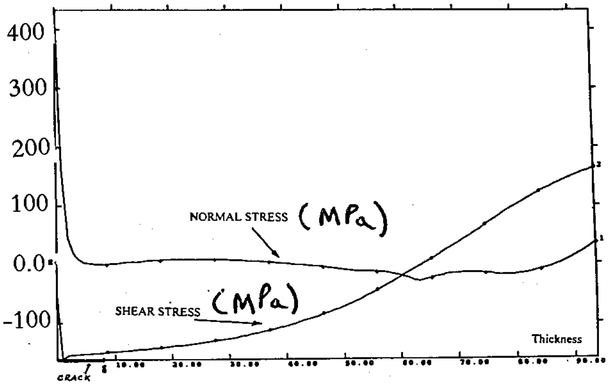

Figure 4

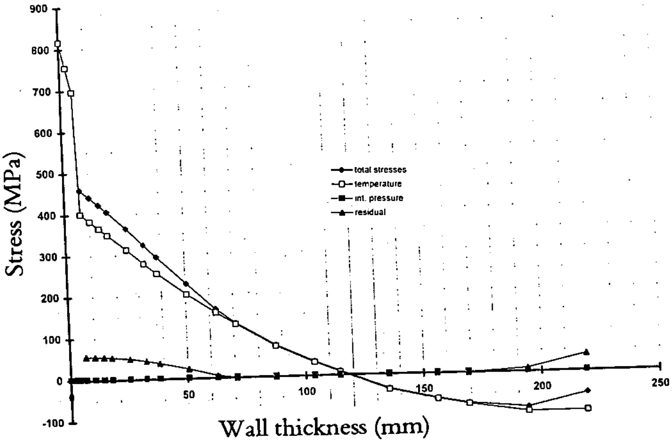

Figure 5